

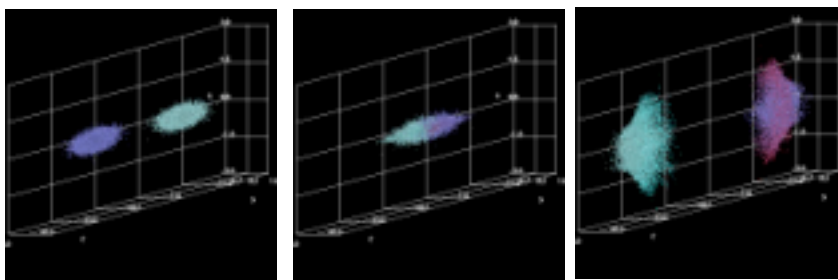
# Developing Extraordinary Tools for Extraordinary Science...



*Notes on layout: This should be thought of as a manuscript for input to a professional designer at TEID, rather than as an indication of the final format. An idea I had for the cover was to use the photo of Lawrence with his first cyclotron as a background screen, and the small photos of the ALS, the OASIS Lab, the IBM/SP, and the Lab logo in the corners. But that too is just an idea at this point. Finally, text in this color/format indicates an aside to the reviewers and designers and is not meant to appear in the final document. -jc*

Much has changed in the eight decades since Ernest Orlando Lawrence invented the cyclotron, but his namesake laboratory in Berkeley remains committed to leadership in accelerator science and technology. While operating and enhancing state-of-the-art facilities like the Advanced Light Source, LBNL researchers are extending the frontiers of accelerator science through participation in projects such as the Large Hadron Collider; the design of future accelerators like a “fourth generation” light source and “drivers” for heavy ion fusion; and the development of advanced accelerator concepts based on lasers and plasmas. Advanced computing is playing a key role in LBNL’s accelerator programs.

## ...through the synthesis of Accelerator Science and Advanced Computing

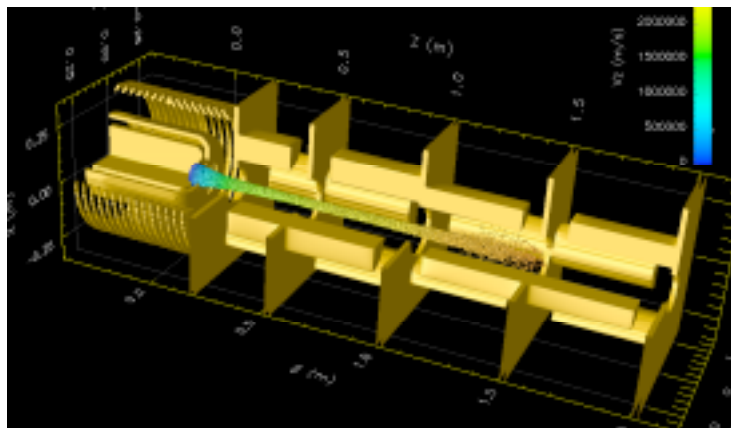


Large-scale simulations performed on NERSC’s IBM/SP supercomputer (right) are helping to improve the performance of existing colliders like the Fermilab Tevatron and to prepare for new machines like CERN’s Large Hadron Collider. The three figures on the left show a collision between two bunches of particles modeled using a new, parallel beam-beam simulation code developed at Lawrence Berkeley National Laboratory. **Credit line:** J. Qiang (AFRD) and Cristina Siegerist (NERSC).

**PARTICLE ACCELERATORS** are critical to research in many fields—in fact, they are relevant to all four strategic elements in the science portfolio of the Department of Energy’s Office of Science. The DOE Office of Science (particularly its programs in High Energy and Nuclear Physics, Basic Energy Sciences, and Fusion Energy Sciences), as well as the National Science Foundation, has been responsible for the development of the nation’s major accelerators. Facilities such as high-energy colliders, synchrotron light sources, and spallation neutron sources are critical to research in many fields, including high energy physics, nuclear physics, materials science, chemistry, and the biosciences.

Accelerators also play current and proposed roles in addressing national needs related to the environment, energy, and national security. Smaller-scale applications of particle accelerators and the technologies associated with them are also highly beneficial to society. Examples include irradiation and sterilization of biological hazards, medical isotope production, particle beams for medical irradiation therapy, superconducting magnets for medical MRI, ion implantation, and beam lithography. All told, particle accelerators have had, and will continue to have, a profound impact on scientific and technological progress and on the quality of people’s lives.

**Lawrence Berkeley National Laboratory** is playing a major role in developing a new generation of computer codes for the terascale era and the upcoming *ultrascale* era of high performance computing. (Ultrascale supercomputers – expected by 2005 – will achieve a performance of more than 100 trillion operations per second, or Tops.) Within LBNL, several organizations are collaborating to develop these new capabilities. The organizations include the Accelerator Modeling and Advanced Computing Program, the Center for Beam Physics, and the Heavy Ion Fusion Virtual National Laboratory in the Accelerator and Fusion Research Division; the Advanced Light Source Division; the Computational Research Division; and the National Energy Research Scientific Computing Center (NERSC). LBNL is also a co-lead laboratory on a SciDAC accelerator modeling project. Through these and other projects, LBNL is developing a new generation of accelerator modeling codes in collaboration with several national laboratories and universities. LBNL’s work has two main areas of emphasis: development of beam dynamics codes, and development of codes for simulating advanced accelerator concepts.



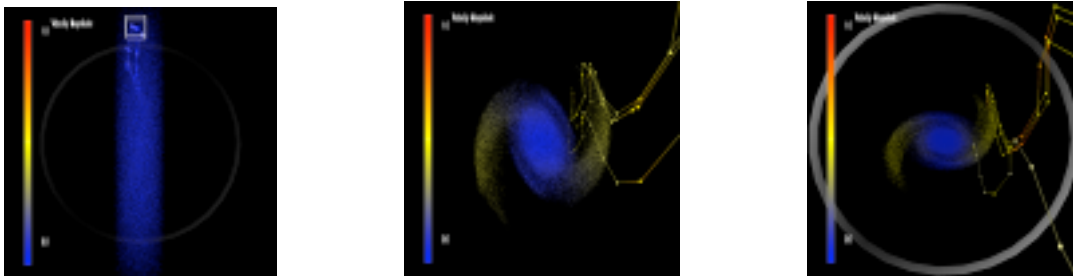
*The applications of accelerators extend far beyond their origins in high-energy and nuclear physics. This is a frame from a WARP3D simulation of an intense, high-current, space-charge-dominated heavy-ion beam’s progress through the High-Current Experiment. The HCX is the present step in a program, performed jointly with Lawrence Livermore National Laboratory and Princeton Plasma Physics Laboratory, to develop heavy-ion accelerators as efficient and cost-effective “drivers” for inertial fusion energy. This 3D time-dependent simulation, from the ion source through a series of electrostatic quadrupole focusing elements, was performed on a terascale computer. On an ultrascale computer at a sustained performance of 100 Tops, end-to-end simulation of a full scale driver is expected to require approximately 20 hours of computing time.*

*Cheryl, this may be cropped, etc. – the accelerator & beam are the interesting parts. Credit line?*

## Simulation Studies of Beam Dynamics

Today's major accelerator facilities are already some of the largest and most complex of all scientific instruments. The next generation will present even greater challenges as designs expand the frontiers of beam intensity, beam energy, and system complexity. The three-dimensional, nonlinear, multi-scale, many-body, and time-dependent characteristics of future accelerator design problems, and the complexity and immensity of the associated computations, add up to extreme technical difficulty. High performance computing has rapidly gone from desirable to indispensable for enhancing existing facilities, designing the next generation, and exploring advanced concepts.

As particle beams are accelerated and focused, they undergo tremendously complicated interactions with their environment. This environment includes the electromagnetic fields of the accelerator (including wakefields), the beam itself (e.g., space-charge effects and intrabeam scattering), fields from other beams (as in a collider or a multi-beam fusion driver), interactions with secondary particles (for example, the electron-cloud effect), and interactions with radiation fields. These phenomena can produce beam halos, degrade the beam quality, and result in beam instabilities that limit accelerator performance. Working with institutions such as LANL, FNAL, BNL, UCLA, and U. Maryland, LBNL is developing a new generation of multi-physics beam dynamics codes to model these and other effects on parallel computers. The codes include IMPACT (a high-intensity linac simulation code), MaryLie/IMPACT (which will extend IMPACT's capabilities to circular machines), BeamBeam3D (a code for modeling colliding beams), and Langevin3D (for the self-consistent simulation of intrabeam scattering and electron cooling systems).



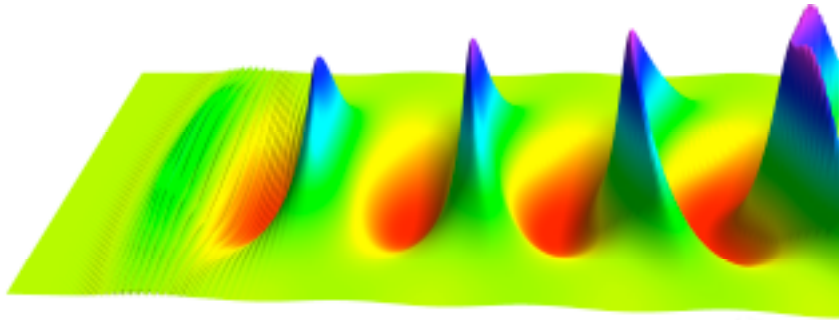
*In these frames showing the time-dependent density evolution of an intense beam, the high density region is the beam core. Selected particles of interest, depending on the physical problem under study, are shown as streamlines. In this case, the streamlines correspond to halo particles in a very low density region far from the core. The spiral arms show the result of the beam being improperly injected into the accelerator, which in this case is a separated sector cyclotron. **Credit line:** Andreas Adelman and Cristina Siegerist (NERSC)*

*[Here I need to capture three likely-looking stages from Miguel's animated GIF of ECE]*

*The “electron-cloud effect” is one of many phenomena that were only recently discovered, or hitherto could be neglected, that have taken on importance in some of today's accelerators and will take on even greater importance in future accelerators. Electron-cloud instabilities are important in today's high intensity proton rings (like the LANL PSR) and B-factories (PEP-II and KEK-B). They will be important in future machines like the SNS accumulator ring and the LHC. This simulation shows, from left to right, a sequence of frames from a simulation showing the buildup of the electron cloud, a buildup so great that it can disrupt the main beam being accelerated. **Credit line:** Miguel Furman, AFRD.*

## Simulation of Advanced Accelerator Concepts

Since high energy accelerators cannot grow in size indefinitely, it will be necessary to develop new technologies capable of higher acceleration gradients. One possible approach is to use the extremely high fields that can be generated in lasers and plasmas. If these benchtop experiments could be developed into useable accelerators of much smaller size than today's, the payoff would be immense, not only in high-energy physics but in wide-ranging applications of compact accelerators to scientific research, industry, and medicine. Thanks to the confluence of successful small-scale experiments, terascale computing resources, and parallel 3D codes for modeling laser/plasma accelerators, it is now possible for full-scale simulations to play a pivotal role in guiding experiments. In addition, the fundamental physics inherent in ultra-intense laser and beam-plasma interactions is rich in nonlinear, ultrafast, and relativistic physics. The insight gained from large-scale particle-in-cell codes is essential for unraveling this new physics.



One of Berkeley Lab's areas of excellence is theoretical, computational, and experimental research on advanced laser-driven plasma-based accelerators. These devices are capable of sustaining ultrahigh accelerating gradients (10-100 GV/m, some three orders of magnitude beyond conventional technology) at their present laboratory scale, and are promising candidates as future compact high-energy accelerators and as drivers for novel short-pulse radiation sources. The accelerating field comes from an electron density wave generated by the radiation pressure of a high-intensity laser pulse moving through a plasma. The centerpiece of the experimental program at l'OASIS Laboratory (Laser Optics and Accelerator Systems Integrated Studies) is a 10 TW, 50 fs, 10 Hz Ti:sapphire laser system. The laser is now being upgraded to 100 TW. The highly nonlinear laser-plasma interaction is modeled numerically with relativistic fluid-Maxwell codes and with particle-in-cell codes. Here we see a simulation of the plasma density wave (propagating from left to right after being excited in the wake of a high-intensity laser pulse), obtained from a fluid code. **Credit line:** Bradley Shadwick, Chemical Sciences Division, and Eric Esarey, AFRD.

## Conclusion

The long-term dream for the upcoming ultrascale era is an array of simulation codes that together provide complete end-to-end modeling of all the important phenomena in an accelerator. LBNL's state-of-the-art accelerator modeling capabilities are helping to make this dream a reality. New simulation codes being developed will assist important design decisions so as to reduce cost and risk, optimize performance, and help assure successful completion on schedule and within budget. The complexity of future accelerators, the performance parameters required by their scientific objectives, and the financial stakes demand it.

For more information on how advances in computer techniques are being put to use in the particle-accelerator field by Berkeley Lab and its collaborators, including links to technical papers and movies of many of these simulations, please visit the Accelerator Modeling and Advanced Computing (AMAC) program website at <http://amac.lbl.gov>, or contact Robert Ryne, AMAC Program Head, at [RDRyne@lbl.gov](mailto:RDRyne@lbl.gov)

*And in fine print at the bottom of the last page we have whatever administrative information needs to go on this kind of document per TEID.*

## *The Fifth Page Of The Four-Page Brochure*

*This is an element that I'll have to work with TEID to fit into the envisioned four-page document. Accordingly, I've pre- designated potential cuts. To write it, I cribbed fr... er, leveraged the existing investment of*

*[http://www.als.lbl.gov/als/science/sci\\_archive/freqmap.html](http://www.als.lbl.gov/als/science/sci_archive/freqmap.html)*

At LBNL's Advanced Light Source, the electron beam in the storage ring normally has small (sub-mm) and stable horizontal and vertical oscillations. It is important to predict and avoid resonances that would cause make these oscillations large, irregular, or chaotic and cause loss of particles. ALS accelerator physicists have collaborated with Jacques Laskar, an astronomer at France's Bureau des Longitudes, on storage-ring applications of his technique of studying the global dynamics of multidimensional systems through frequency-map analysis. They have demonstrated that the generation of frequency maps, using beam positions measured on each revolution around the ring, sensitively reveals the strength of harmful resonances. *[begin possible cut]* The calculation of the frequency maps involves numerical integration of the equations of motion with a fast-converging modified Fourier technique to obtain a quasi-periodic approximation to the calculated trajectories from which the fundamental frequencies are extracted. In the case of a storage ring, the fundamental frequencies correspond to the tunes. *[ending of one possible cut]* These frequency maps are based on the ideal ALS lattice (top) and measurements from the actual machine with its experimentally measured magnetic-field imperfections. Frequency map techniques are now seen as extremely valuable tools for determining the optimal operating points (machine settings) of light sources. The techniques are so powerful that, in the future, it is likely that they will be integrated into on-line control systems. *[ending of the other possible cut]* Blue areas represent electron trajectories with no diffusion (no change in betatron tune), and red areas represent particles with high rates of diffusion. *[if push really came to shove in our quest to push and shove the core content into the available space, we could just use the "real" map and omit the ideal-lattice map. -jc]*

